Proposed Test Procedure Modifications to Address PHEVs

California Air Resources Board

Mobile Source Control Division

Public Workshop

April 8, 2008

California Environmental Protection Agency
AIR RESOURCES BOARD

Overview

- Scope & Objectives
- Outputs for ZEV Regulation
- Existing Test Procedure Issues
- Proposed Exhaust TP Modifications
- Proposed Evaporative TP Modifications
- Schedule
- Summary

Scope & Objectives

- To incorporate test procedures for PHEVs
  - » Address the types of architectures
  - » Adequately address emissions from PHEVs
  - » Assess their relative value in the ZEV Reg.
- Align with SAE & US EPA modifications
  - » When possible
  - » Minimize burden to mfrs.

Definitions

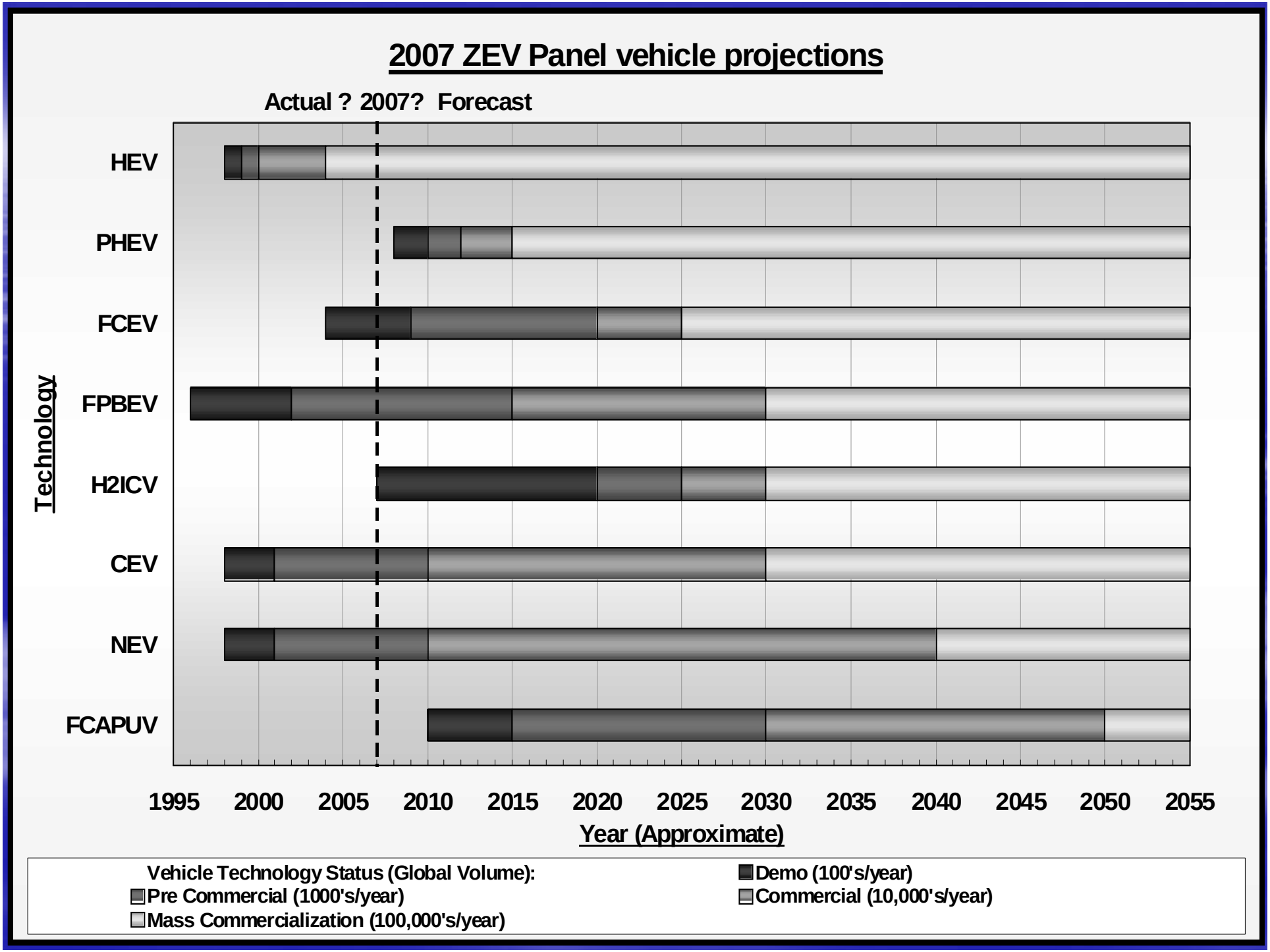
- Off-vehicle charge capable
  - » Plug-in Hybrid Electric Vehicle (PHEV)
  - » Having the ability to charge battery from an external source
  - » Utilizes an internal combustion engine (ICE) and battery to operate the vehicle
- Blended operation
- Non- blended operation

HEV Test Procedure "Outputs" Required for the ARB ZEV Regulation

Craig M. Childers

ZEV Regulation

- First Adopted 1990
- Took effect in 2005
- Adopted by several states besides CA
- 2008: First modifications since implementation in 2005
  - » ZEV Independent Expert Panel Technical Review 2007
  - » Test Procedures need refining when
    - vehicles are significantly “different”, and
    - designed and planned for production levels > 10K


2007 ZEV Panel vehicle projections
Actual ? 2007? Forecast
HEV
PHEV
FCEV
FPBEV
H2ICV
CEV
NEV
FCAPUV
Technology
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Year (Approximate)
Vehicle Technology Status (Global Volume):
Demo (100's/year)
Pre Commercial (1000's/year)
Commercial (10,000's/year)
Mass Commercialization (100,000's/year)

2007 ARB Expert Panel

Plug-in HEVs (PHEVs)

- Battery may be fully used daily to accelerate fuel savings payback
- "Blended PHEVs derived from existing HEVs are more likely in early products and will proliferate rapidly"
- PHEVs are Advanced Technology PZEVs (AT-PZEVs)

AT PZEV
Overall Credit Calculations

AT-PZEVs earn PZEV base credit of 0.2 plus allowances for:

- Advanced ZEV Componentry
- Zero Emission Range (ZER)
- Low Fuel Cycle Emissions

AT PZEV Credit = 0.2 Base + Advanced Componentry + ZER + Low Fuel Cycle Emissions

From TP

AT-PZEV:
Advanced Componentry

- Phased out two former categories,
- Added a new one “Type F”

Year	Type C 10 kW	Type D 10 kW	Type E 50 kW	Type F (NEW) >= 10 mile UDDS Capable
2005-2011	0.2	0.4	0.5	0.85
2012-2014	0.15	0.35	0.45	0.8
2015+	0.1	0.25	0.35	0.7

2008 ZEV Regulation Modifications: AT-PZEV Zero Emission VMT

- **Terms**
  - » EAER = Equivalent All Electric Range
  - » ERF = Electric Range Fraction
  - » Rcd = Charge Depletion Range (actual)

2008 ZEV Regulation Modifications: AT-PZEV Zero Emission VMT

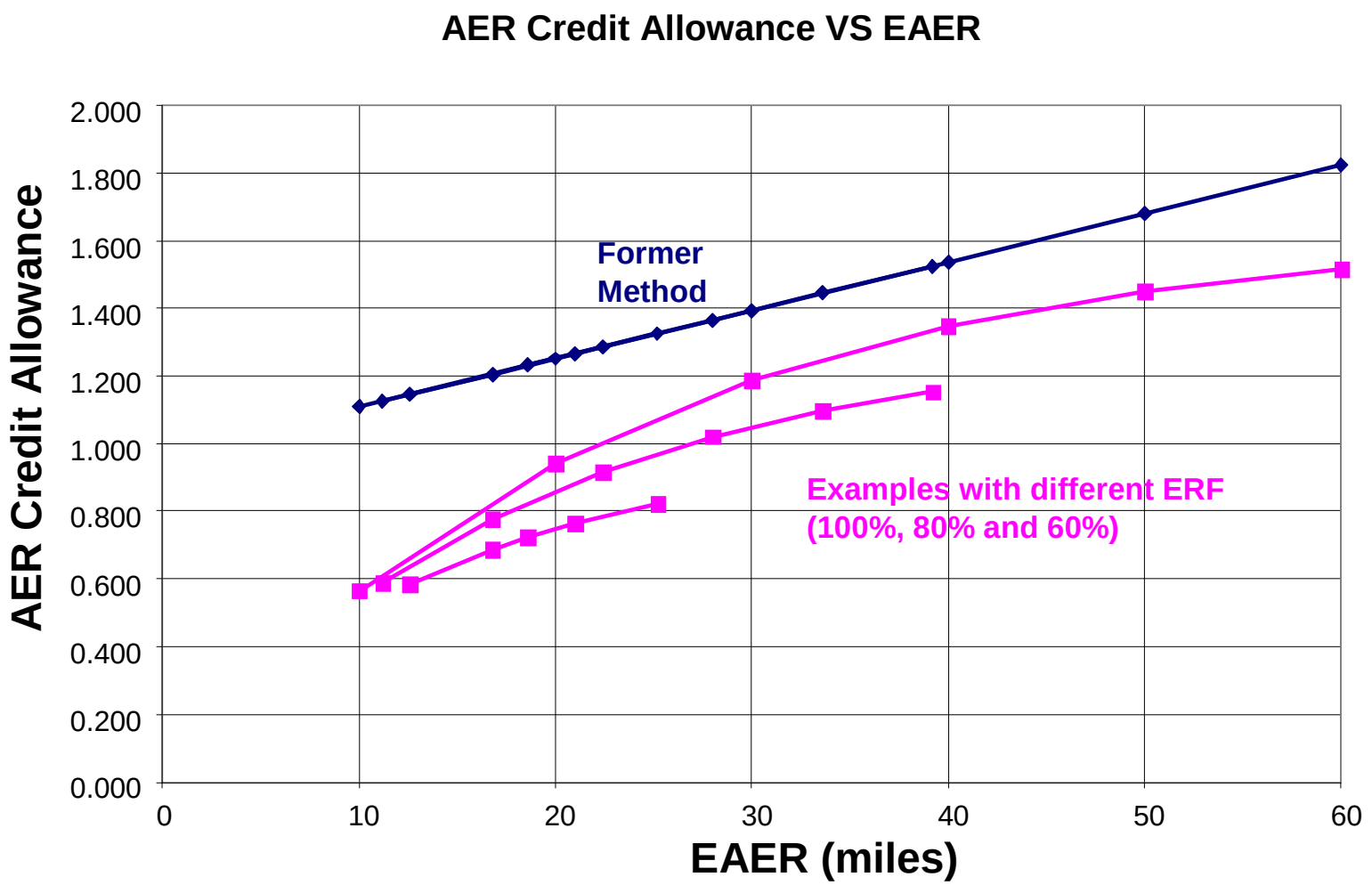
Formulas

EAER = (Rcd * ERF)

Former Allowance = (33.8 + [0.5 * AER])/25)

New Allowance = (EAER/14.6) * (1 – UF_{Rcd})

2008 ZEV Regulation Modifications:
AT-PZEV Zero Emission VMT



2008 ZEV Regulation Modifications:

AT-PZEV Total Credit

Type	Rcd		ERF (%)	2011 Allowance	
				Existing	Proposed
Blended PHEV	12.5	B12.5	80	0.7	1.24
Blended PHEV	20	B20	80	0.7	1.45
Blended PHEV	30	B30	80	0.7	1.65
Blended PHEV	40	B40	80	0.7	1.78
AER PHEV	10	P10	100	1.9	1.62
AER PHEV	20	P20	100	2.1	1.99
AER PHEV	40	P40	100	2.4	2.4
AER PHEV	60	P60	100	2.7	2.57

Summary:

HEV TP Outputs Needed for ZEV Reg.

- EAER
  - » Either as output, or
  - » R_{cd}, ERF (to calculate EAER)
- R_{cd} (actual)
- US06 AER capable?
  - » yes/no
  - » range

ZEV Reg. Contact Info

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Outputs for ZEV Reg Discussion

Proposed PHEV Exhaust Test Procedure

Jeff Wong

Current Test Procedures

CA Exhaust Emission Standards & Test Procedures (Title 13 § xxx)

- Applicable to ZEVs & Hybrid Electric Vehicles
- Originally adopted in 1999
- Last amended December 19, 2003
- Based on 1999 EV, HEV, PHEV technologies
- Includes test procedures for
  - » Zero emission battery electric vehicles,
  - » All-Electric Range extender PHEVs, &
  - » Non-plug-in hybrid electric vehicles.
- Procedures for EVs and non plug-in hybrids still in use today.

Exhaust TP Issues

- Inadequately addresses
  - » Blended PHEVs
  - » All-Electric Range capable PHEVs
    - real world driving conditions
    - subsequent emissions impact
- Updates to definitions
  - » “charge depleting”
  - » “charge sustaining”
  - » references to a particular vehicle’s control system from 1998.

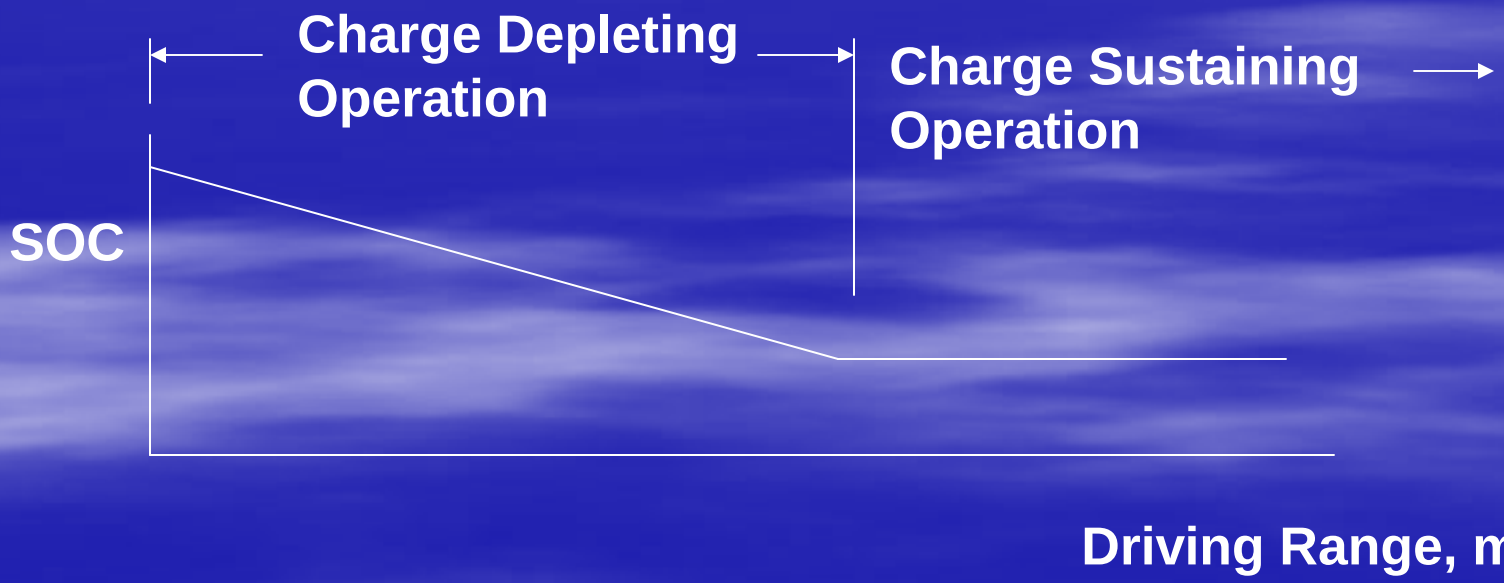
Objectives

- Establish testing methods that
  - » Characterize the emissions
  - » Supplemental battery range
  - » Applicable to all PHEV designs & architectures
  - » Compatible with existing TP for EV & HEV
- Identify appropriate metrics
  - » For characterizing PHEVs
  - » Fit within existing framework of Ca ZEV Program
- Align with SAE J1711 subcommittee findings
- Align with USEPA
- Avoid added test burden for manufacturers

State Of Charge

Assumptions:

In normal operation, PHEVs will have a charge depleting (CD) mode followed by a charge sustaining (CS) mode of operation.



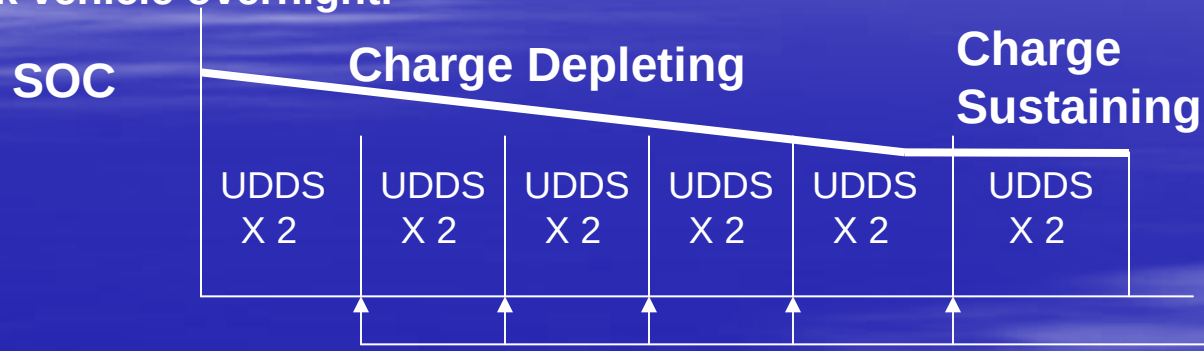
Why ARB Needs to test PHEVs:

Test	Emissions	Electric Range
FTP (UDDS)	NMHC, CO, NOx, CO2, PM	✓
Highway (HWY)	NOx, CO2	✓
US06	NMHC + NOx, CO	
SC03	NMHC + NOx, CO	
Evap Emissions	HC	
Cold CO 20°F	CO	
50°F Cold Start	NMHC, CO, NOx	

Proposed City Test Procedure

Day1:

Cold Soak and fully charge vehicle. Perform continuous UDDS X 2 CD Test(s) followed by a 10-20 minute soak period until charge sustaining operation is achieved for 2 UDDS tests. The combined weighted emissions shall not exceed the emissions standard (See Slide titled "UDDS Bag Weighting for Emissions"). Soak vehicle overnight.

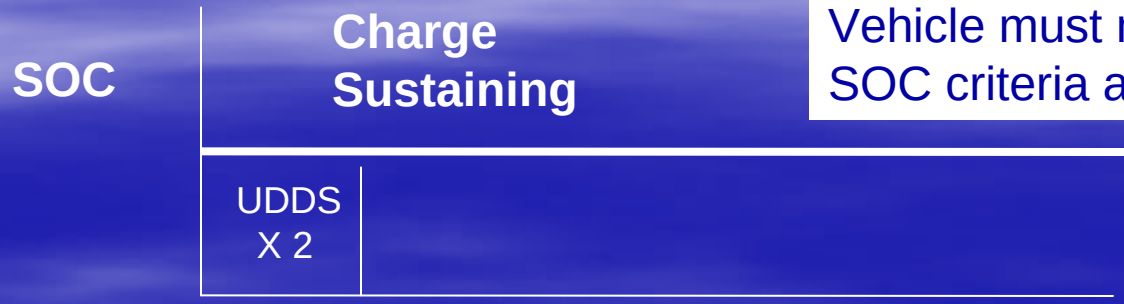


Note: there is a 10 min key-off hot soak between each UDDSX2 test

10-20 min hot soak period

Day 2:

Perform one cold UDDS X2 CS test. The test shall not exceed the emissions standard. The certification emissions value will be the worst case of the either the CD or CS test.

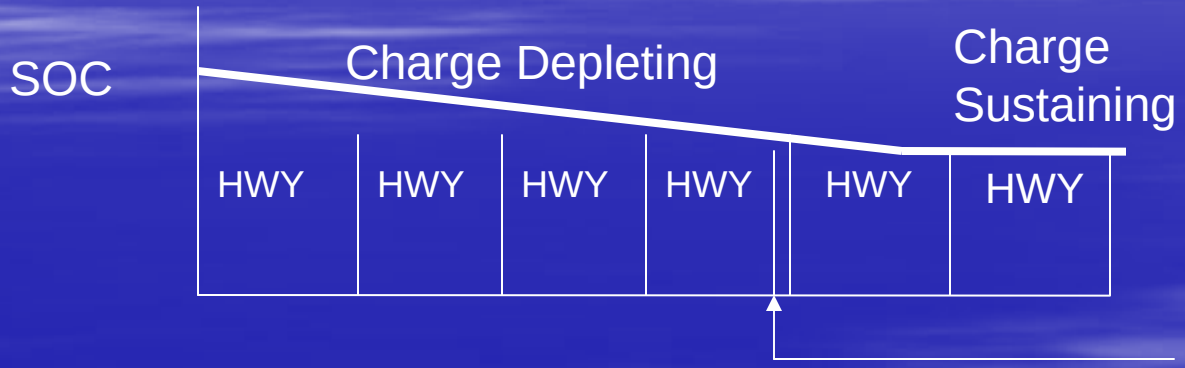


Vehicle must meet 1% fuel energy SOC criteria as standard HEV

Proposed Hwy Test Procedure

Day 1

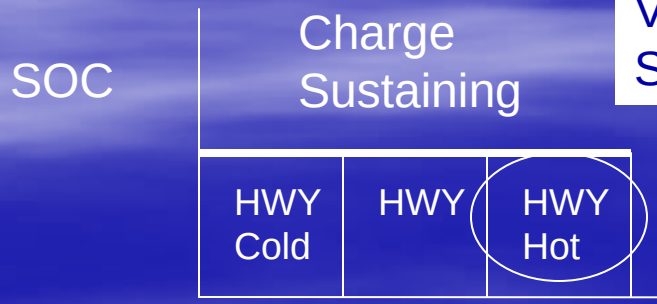
Cold soak and fully charge vehicle. Perform four continuous HWY CD test(s) followed by a 10-30 minute soak period until charge sustaining operation has been achieved and the last HWY test has been completed. Soak vehicle overnight.



Note: there is a 15 sec key-on pause between each HWY test

Day 2

Perform HWY CS test . The hot HWY test shall not exceed the emissions standard.



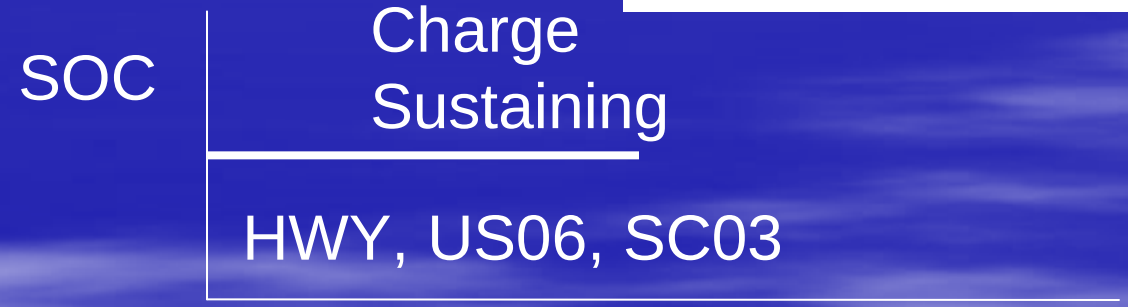
Vehicle must meet 1% fuel energy SOC criteria for Standard HEV

Note: A third 15 key-on pause HWY test is added to the series because one HWY test may not sufficiently stabilize the vehicle

Proposed HWY, US-06, SC03

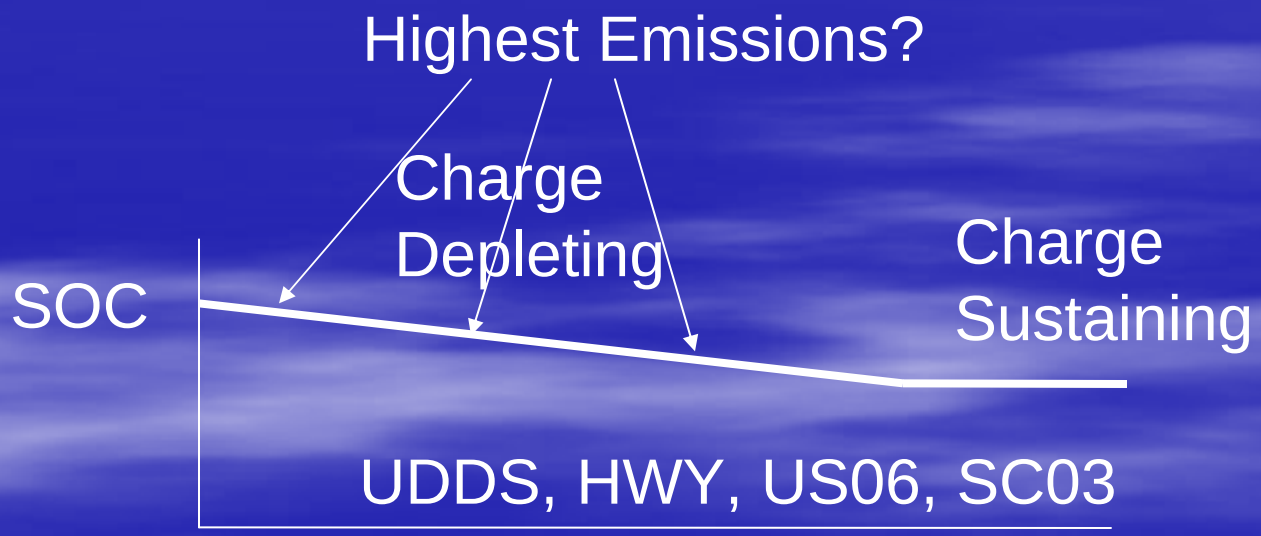
All hot tests conducted in Charge Sustaining Mode

Vehicle must meet 1% fuel energy SOC criteria as standard HEV



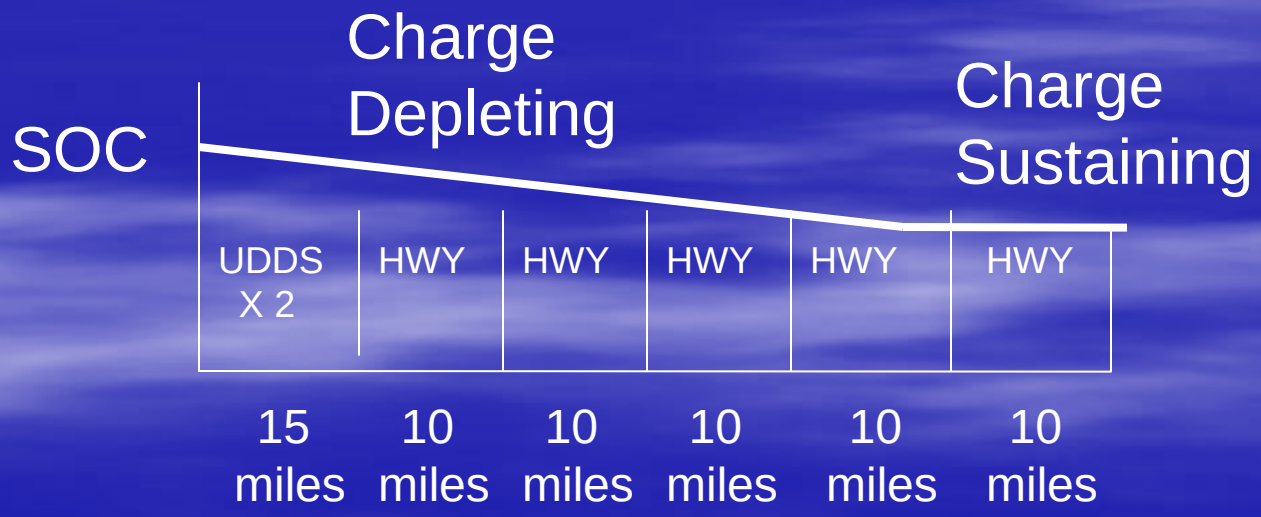
PHEV Exhaust Tests Notes

Confirmatory testing may be needed to establish if higher emissions occur at different states of charge. This is to ensure that cold start and other emissions standards are not exceeded at other operating SOCs.



PHEV Exhaust Tests Notes (Cont.)

Consideration may be made to combine city and highway tests if there is sufficient data to show that combined tests produce equivalent results to separate city and highway tests for vehicles with a charge depleting range of more than 35 miles.



PHEV Exhaust Tests Notes (Cont.)

- Underscores need for OBD accessible SOC/SOE, voltage/current, and CD/CS status indicators and mode selection for technician safety, for repair and diagnostics purposes, and data acquisition during testing.
- SOC/SOE, voltage/current, and CD/CS indicators should adhere to standards which define the measurement technique and accuracy of such readings.
- Means should be made by the manufacturer to access main battery voltage and current for verification purposes without substantial effort.

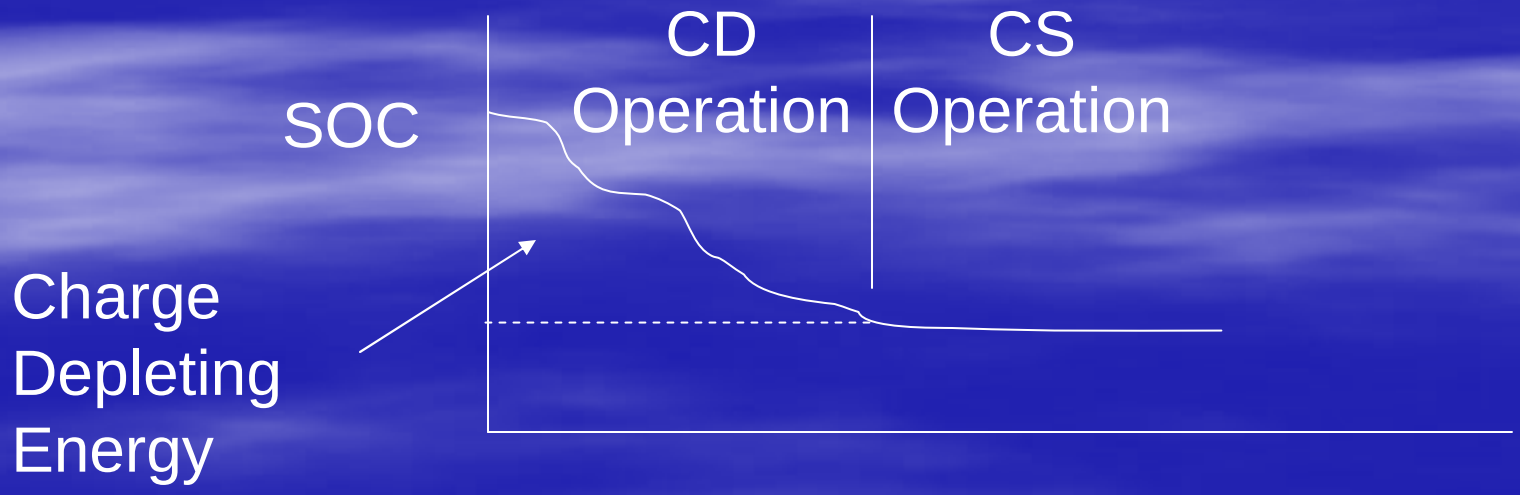
Equivalent All-Electric Range

- A new metric is needed to compare PHEVs that have blended battery electric and internal combustion engine operation with PHEVs that have all-electric range and pure EVs.
- Must be relatively simple to measure and calculate
- Compatibility with existing ARB regulations which specify all-electric range for vehicle categories and incentives*

* Such as qualifying for increased AT-PZEV credits for vehicles with 10 mile or greater ZEV range

Equivalent All-Electric Range Principles

- **Based on the difference of energy between two sources of fuel used for vehicle propulsion under standardized conditions: off-board electricity and a fuel source, such as gasoline.**
- **By measuring the difference in CO2 tailpipe emissions produced between the charge sustaining and depleting operation of the vehicle, the net work produced by the electric motor can be calculated. CO2 is already measured on standard emission test equipment.**



Proposed PHEV Terms

	Abbrev	Units
Charge Depleting Range	Rcd	mi
Charge Depleting Net Energy Consumption	Ecd	wh
Charge Sustaining Net Energy Consumption	Ecs ~ 0	wh
Charge Depleting CO2 Produced	Mcd	g
Charge Sustaining CO2 Produced	Mcs	g
Equivalent All-Electric Range	EAER	mi
Equivalent All-Electric Range Fraction	EAERF	%
Equivalent All-Electric Range Energy Consumption	EAEREC	wh/mi

Proposed PHEV Terms (Cont.)

EAER (mi) = (Mcs-Mcd)/Mcs X Rcd

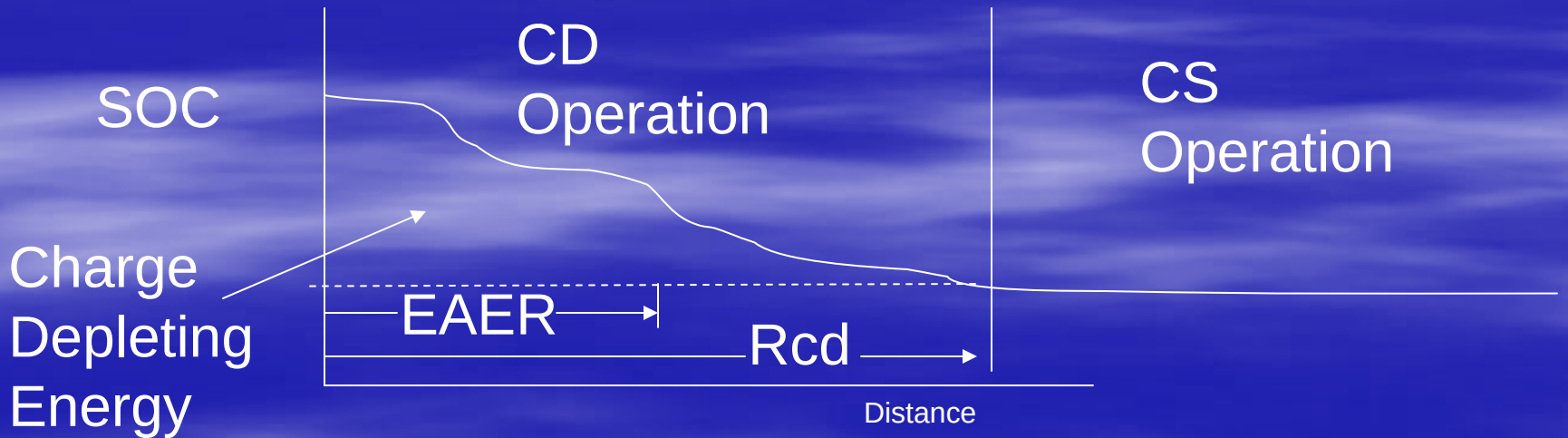
- Mcs and Mcd CO2 evaluated over the Rcd range

EAER Fraction (%) = EAER / Rcd

- Mcs, Mcd, and evaluated over the Rcd range

EAER Energy Consumption (wh/mi) = Ecd / EAER

- Ecs and Ecd evaluated over the Rcd range



"Equivalent All-Electric Range"

Compatible with Existing Hybrid Terminology

Series Hybrid

$$EAER = \left(CO_2\dagger - CO_2\dagger\dagger \right) / CO_2\dagger \times \frac{CD}{miles} = \textbf{CD AER}$$

$CO_2\dagger\dagger$ → 0

Each evaluated over the CD range

Example: *Series PHEV30*

*EAER = (150g - 0g)/150g * 30 mi = 30 miles*

† Measured during Cold start CS operation

†† Measured during CD Operation

Example

Energy CS Toyota Prius PHEV with UDDS X 2
Charge Depleting Range

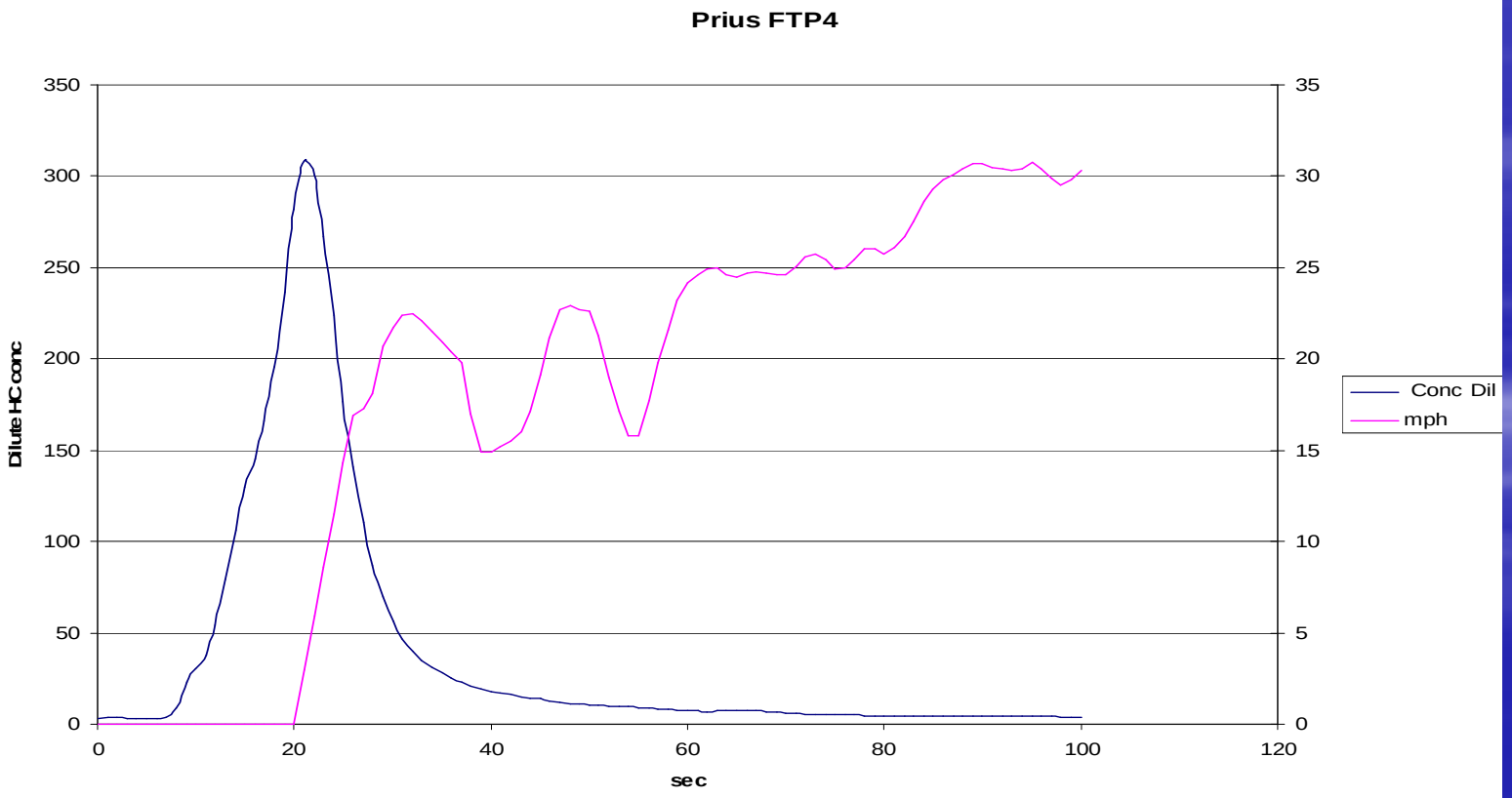
Rcd = 14.9 mi
Ecd = 939 Wh DC, 1104 Wh AC
Ecs ~ 0 Wh
Mcd = 93.5 g
Mcs = 142.2 g

EAER = (142.2g-93.5g)/142.2g*14.9mi = 5.1 mi
EERF = 5.1 mi/14.9 mi = 34%
EAER Energy Consumption = (939 wh - 0 wh) / 5.1 mi
= 184.1 wh/mi DC
= (1104 wh - 0 wh) / 5.1mi
= 216.5 wh/mi AC

Example

2006 Toyota Prius

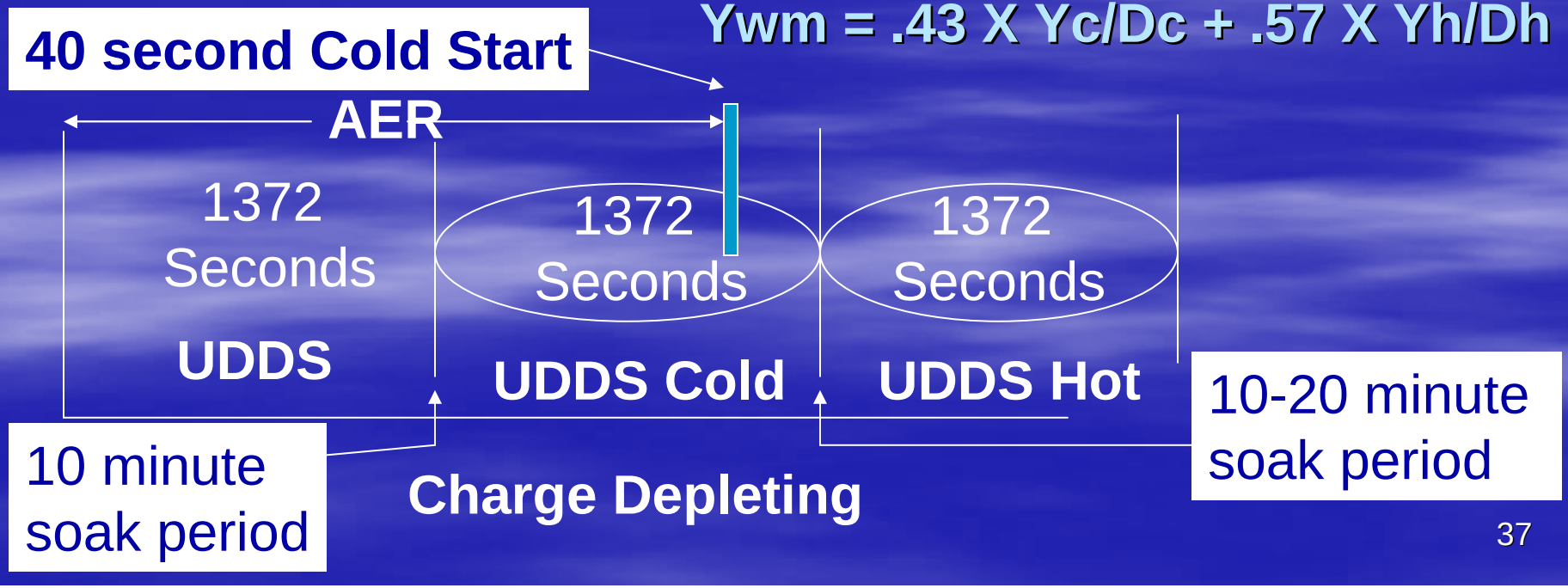
- Cold Start - UDDS Test
- First 120 seconds
- 90% Emissions occur in first 45 seconds after engine start



UDDS Cold Start Emissions

CD Operation

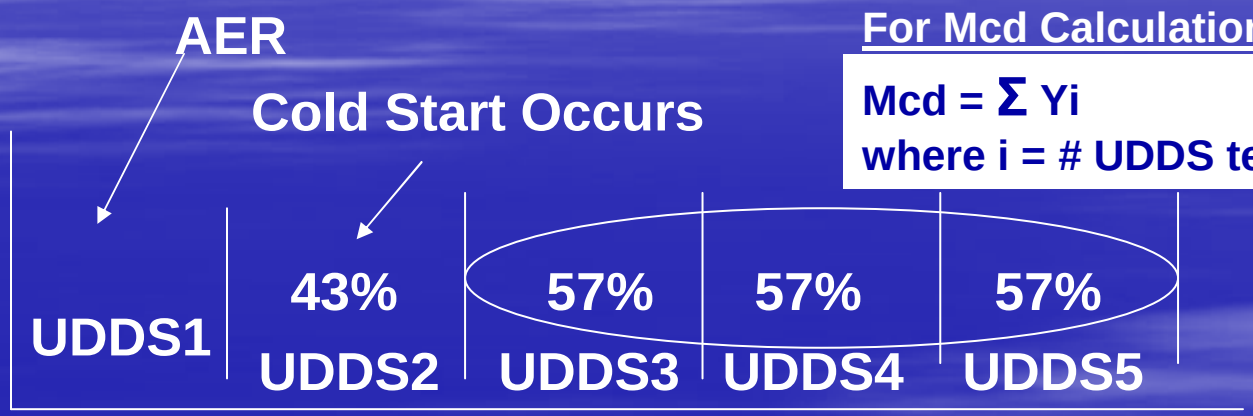
- Cold start UDDS begins at engine start
- Continues until the end of charge depleting range test
- Range extender PHEV requirements change
  - » Separate AER test & emissions test following day
- 97% chance a 40 second cold start completely occurs in a 1372 second UDDS test



UDDS Weighting for Emissions

For Criteria Emissions All Hot Start UDDSs Averaged at 57%

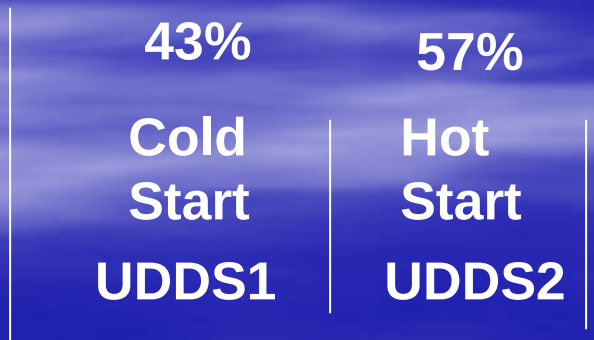
Ywm = .43 X Yc/Dc + .57 X (Σ Yn)/ (Σ Dn)
where n = # hot start UDDS tests CD operation



Charge Depleting

For Mcd Calculations:

Mcd = Σ Yi
where i = # UDDS tests CD operation



Charge Sustaining

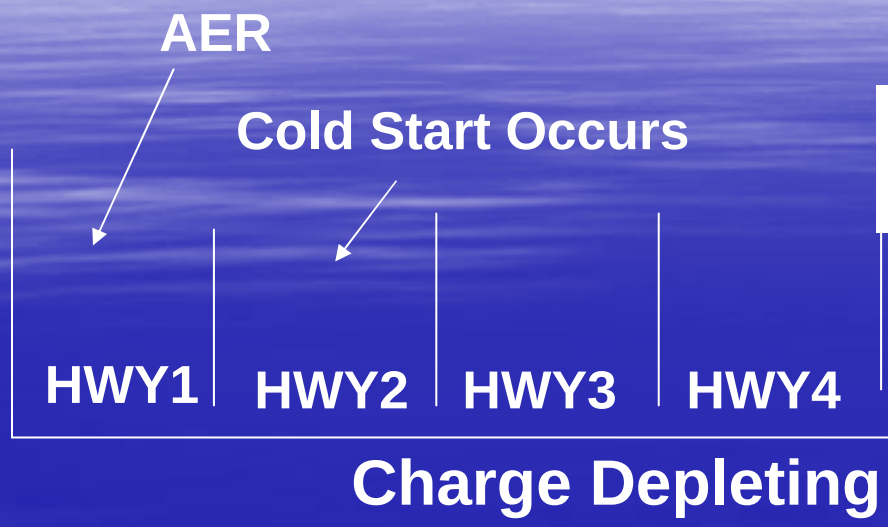
For Criteria Emissions:

Ywm = .43 X Yc/Dc + .57 X Yh/Dh

For Mcs Calculations:

Mcs = ((Rcd/(Dc+Dh)) X (Yc + Yh)

HWY Emission Calculations



For Mcd Calculations:

Mcd = Σ Yi
where i = # HWY tests CD operation

For Criteria Emissions:

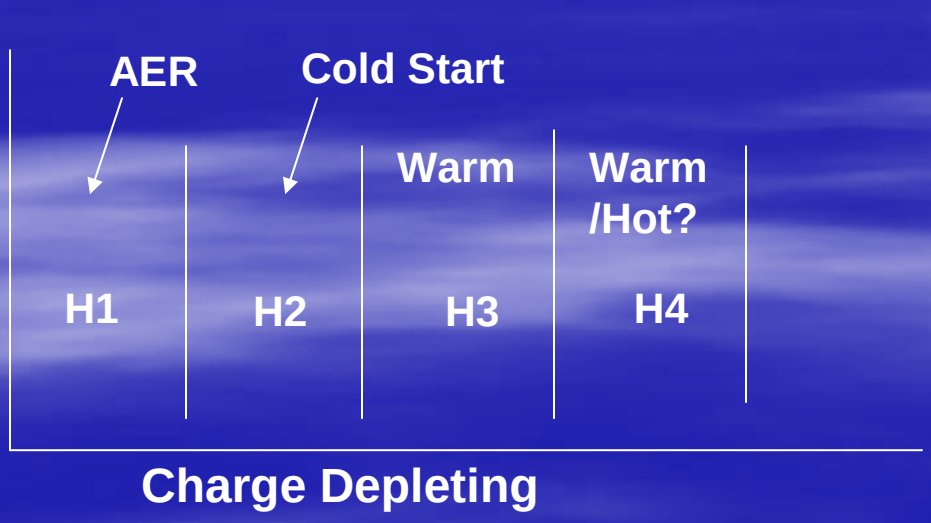
Ywm = Yh/Dh

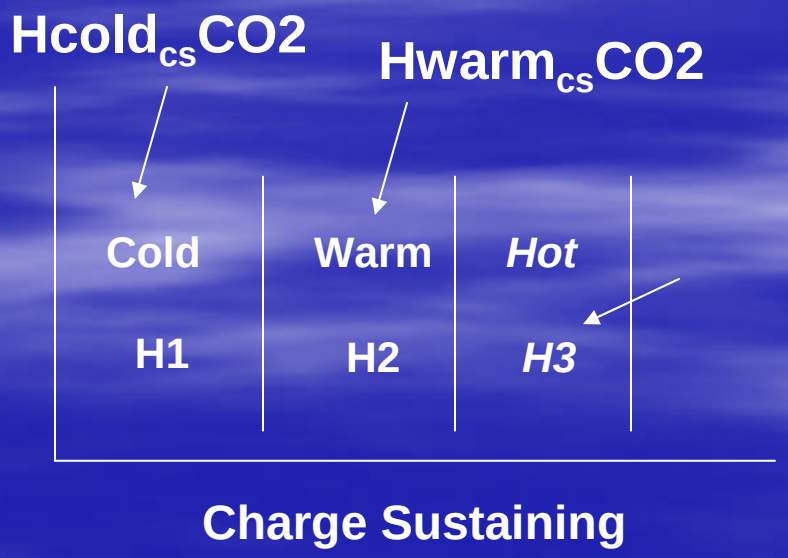
For Mcs Calculations:

Mcs = ((Rcd/Dh) X Yh

Cold Start Hwy CD Correction

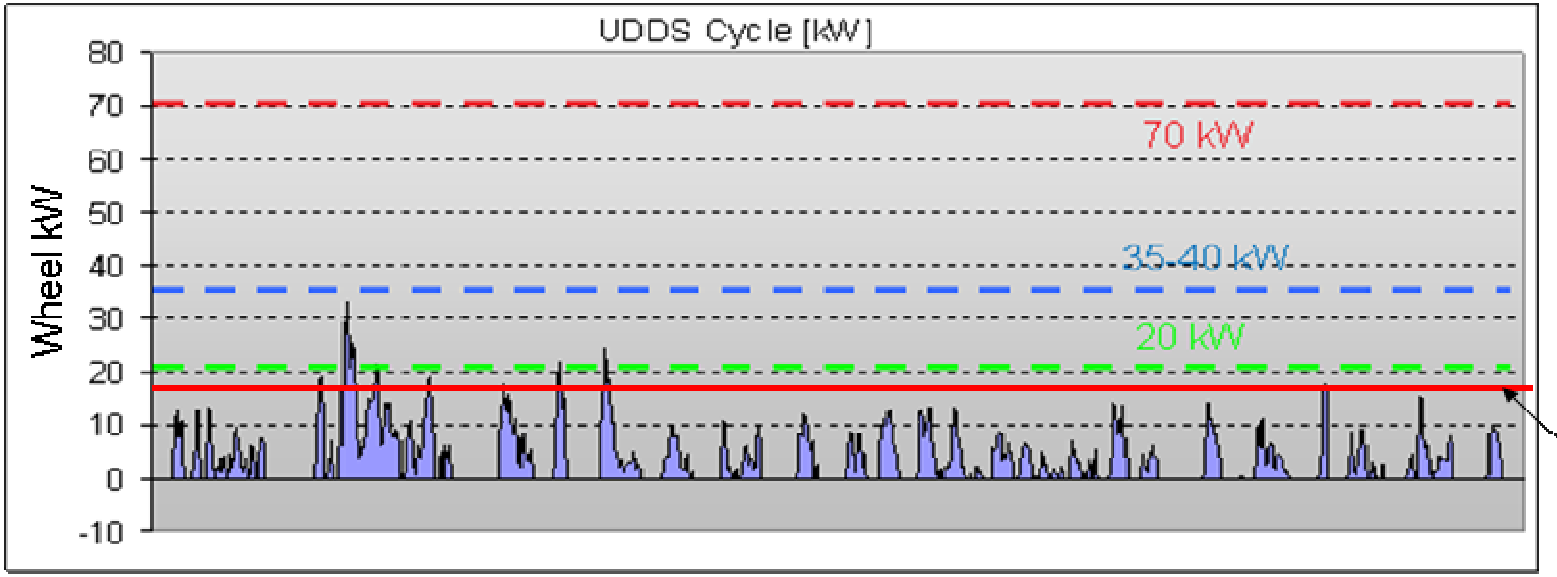
- **Hwy correction**
  - » Hwy Corrected EAER (mi) = (Mcs-(Mcd-CFcd))/Mcs X Rcd
  - » increases Hwy EAER
  - » removes the influence of the cold start event
  - » third CS HWY used for criteria emissions & calc HWY Mcs
- **CD Cold Hwy CO2 Mass Correction, CFcd**
  - » CFcd = (HcoldcsCO2 - HwarmcsCO2)





Possible PHEV Designs

Different PHEV Designs – differentiated by wheel power

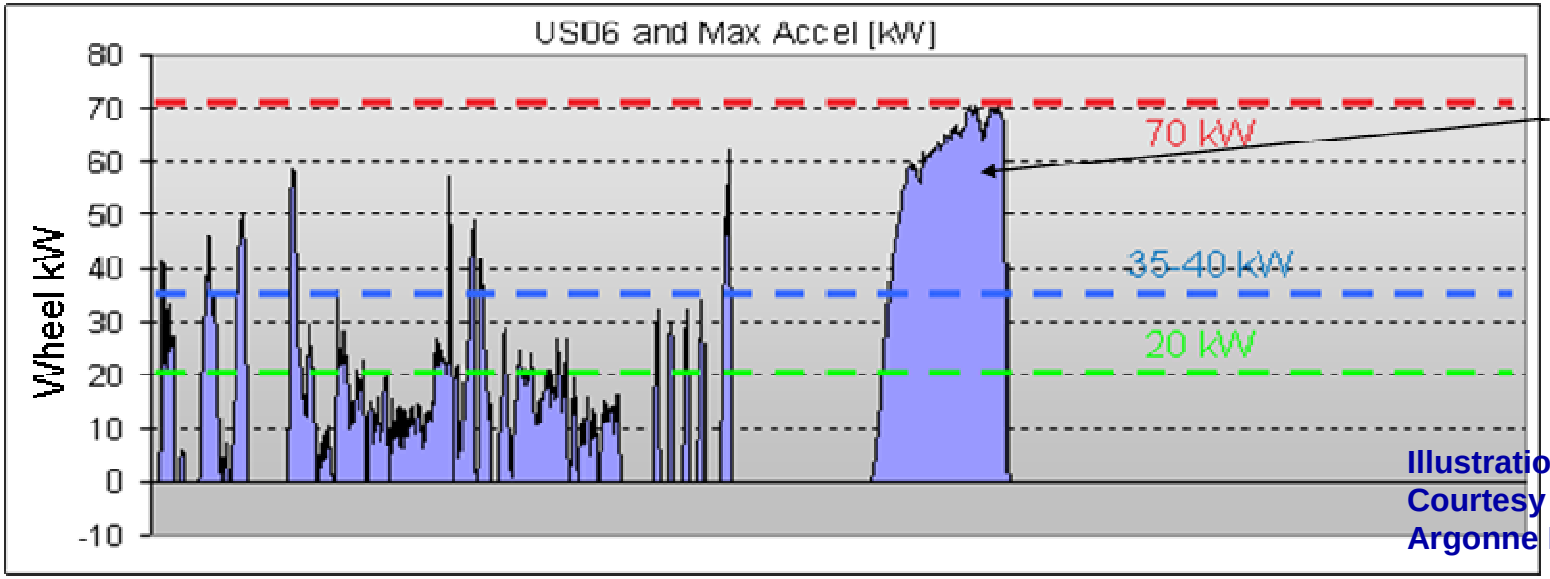


Range-Extender

Intermediate

Blended

Observed 04Prius PHEV Kit Eng On



Full Accel 04Prius

Illustration
Courtesy Mike Duoba,
Argonne National Laboratory

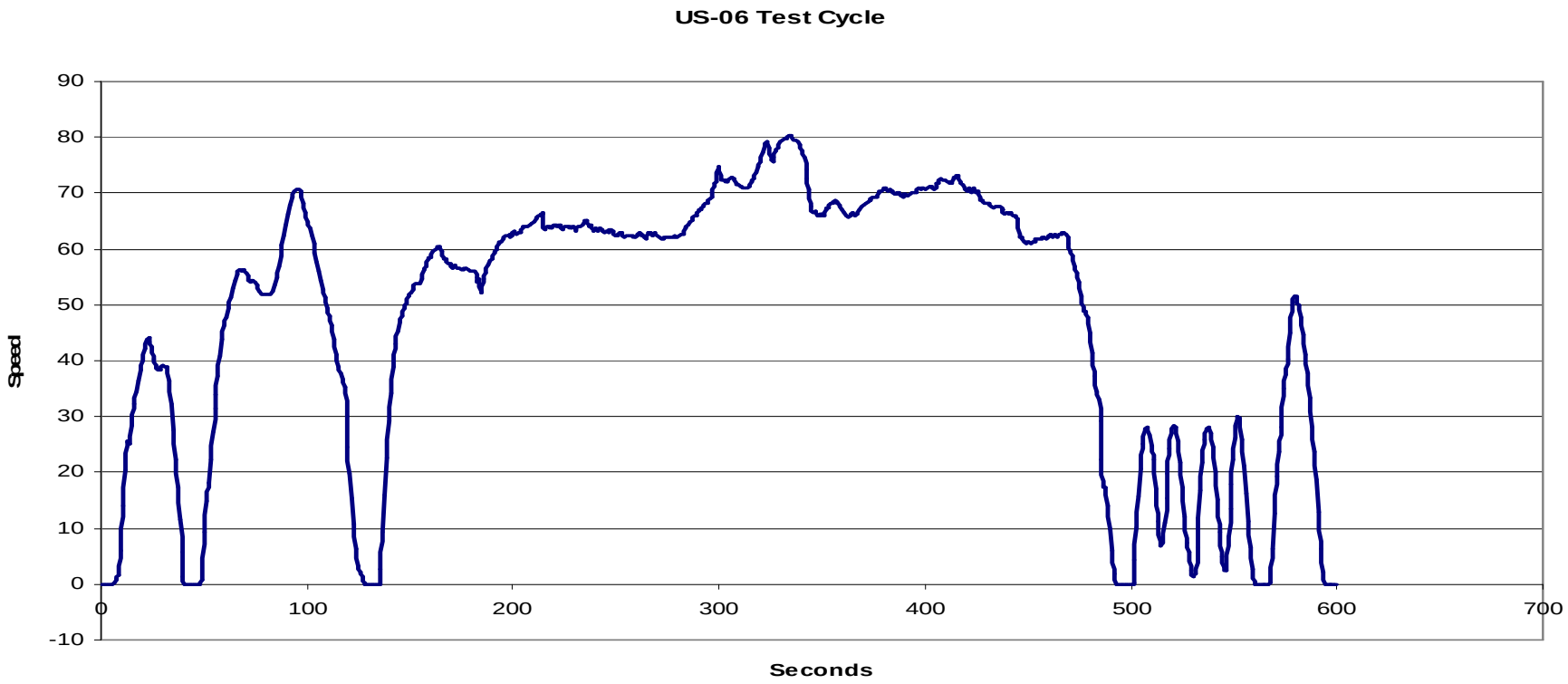
Potential Low Emission PHEV Designs

Low Emissions are Possible Regardless of PHEV Design

- Blended
  - » ICE on at start of emissions test
  - » e.g. Energy CS Vehicle
- Blended Intermediate
  - » ICE on at low load condition for catalyst warm up with full electric motor assist if necessary
- AER Range Extender
  - » ICE on at idle, or
  - » low load condition with full electric motor assist, if necessary
  - » Example: Possible maximum battery energy requirement for a blended intermediate PHEV to achieve a low load ICE cold start during the UDDS assuming an All-Electric 45 second cold start and a worst case 40 kW propulsion requirement
  - » 45 sec X hr/3600 sec X 40kW = 0.5 kWh (~ 1.4 mi @ 350 wh/mi)

Off-Cycle Cold Start Emissions Mitigation

Charge Depleting Operation



Possible Solutions:

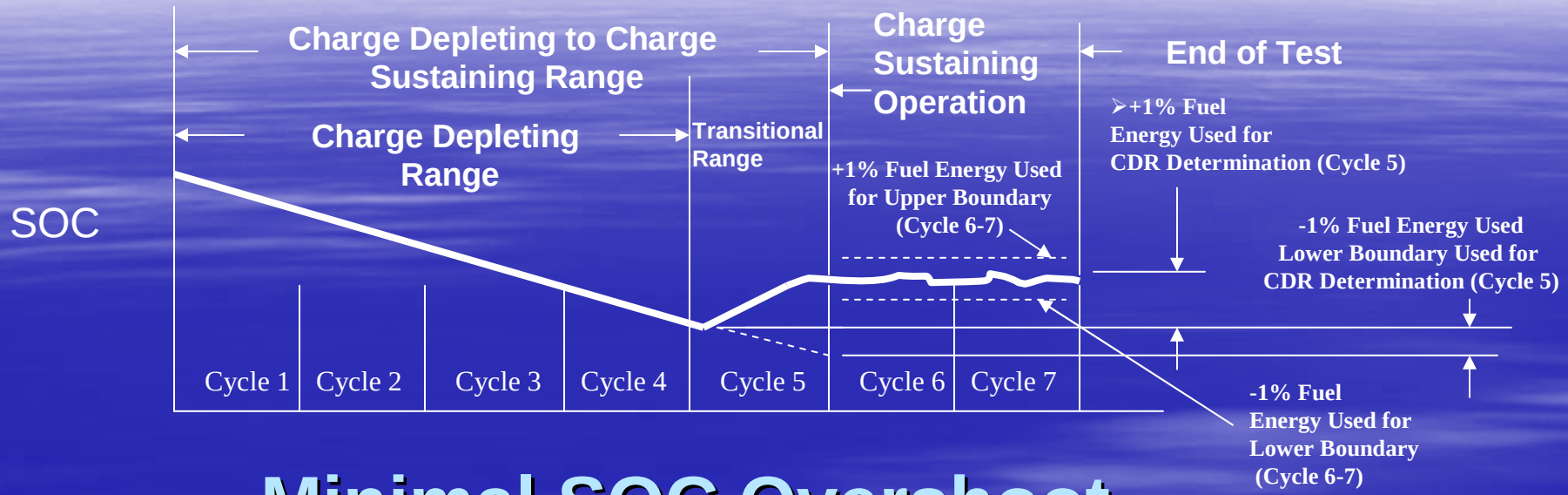
- Engine warm up to heat catalyst at start up and/or during mild accelerations to keep engine/catalyst warm and to reduce emissions during heavy accelerations.
- Allow maximum electric motor assist for all accelerations so that engine load during cold start is kept to a minimum.
- Provide data to show that potential cold start off-cycle emissions are controlled to the extent that they are controlled for the UDDS test.

CD End of Test Criteria

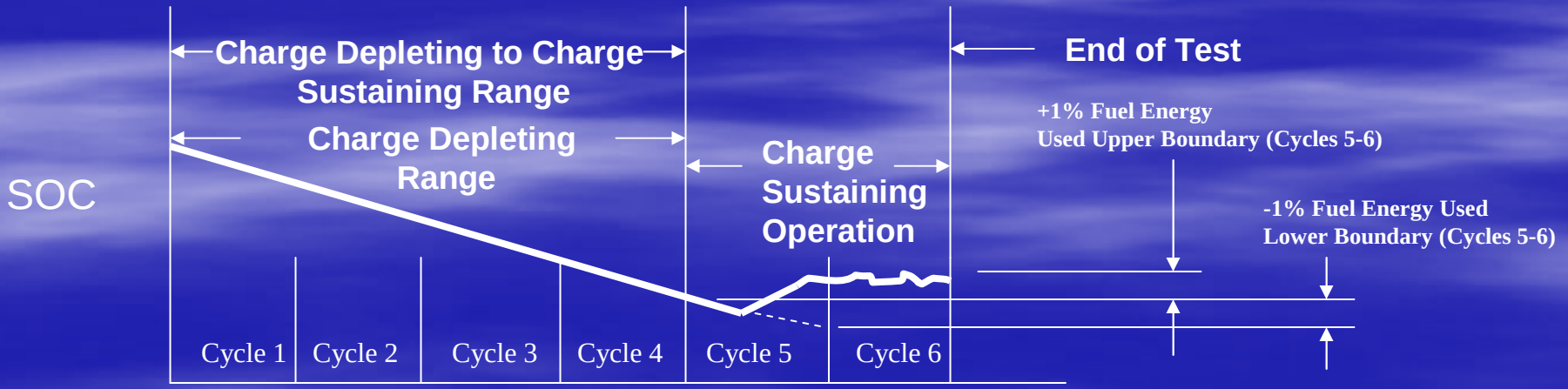
- CD City TP will end when
  - » SOC Net Change Tolerances met for 2 UDDS tests
  - » Indicates CS operation
- Rcdt = sum of distance traveled on CD City TP up to UDDS cycle prior to where SOC is above lower bound SOC tolerance for one test cycle given by the following:
  - » $(\text{Amp-hr}_{final})_{min} = (\text{Amp-hr}_{initial}) - 0.01 * \frac{(NHV_{fuel} * m_{fuel})}{(V_{system} * K1)}$
- CD HWY TP will end when
  - » SOC Net Change Tolerances met for one HWY test
  - » Indicates charge sustaining operation
- Rcdt = sum of distance traveled on CD City TP up to HWY cycle prior to where SOC is above lower bound SOC tolerance for one test cycle by the following:
  - » $(\text{Amp-hr}_{final})_{min} = (\text{Amp-hr}_{initial}) - 0.01 * \frac{(NHV_{fuel} * m_{fuel})}{(V_{system} * K1)}$

City End of Test Conditions

Moderate SOC Overshoot

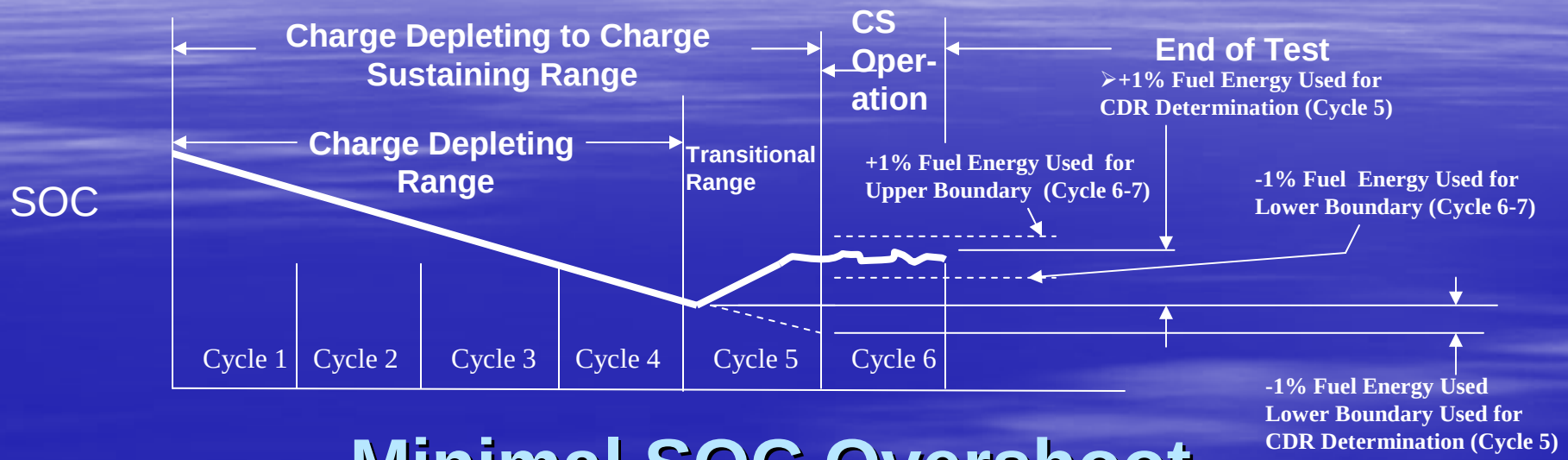


Minimal SOC Overshoot

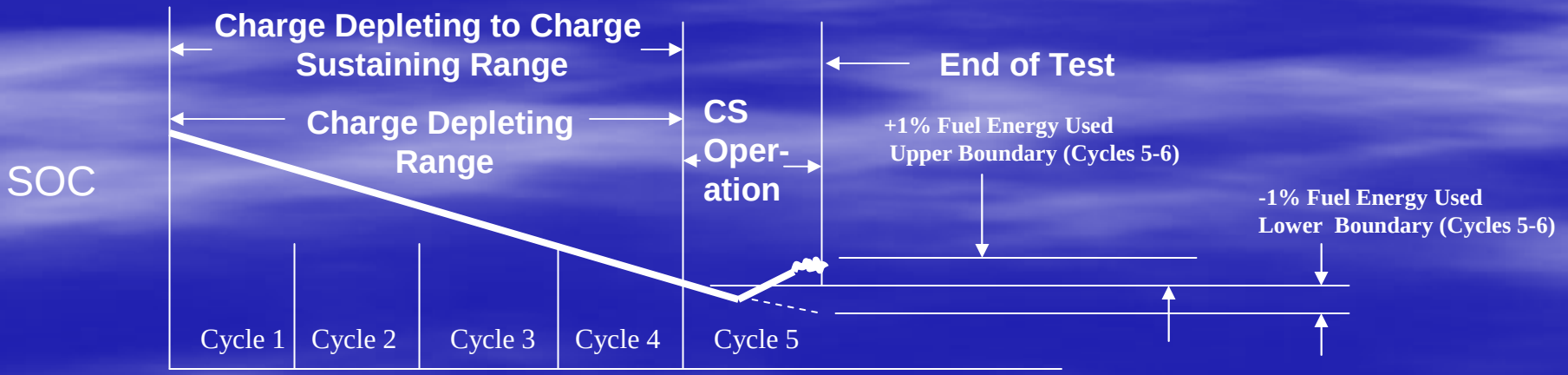


Hwy End of Test Conditions

Moderate SOC Overshoot

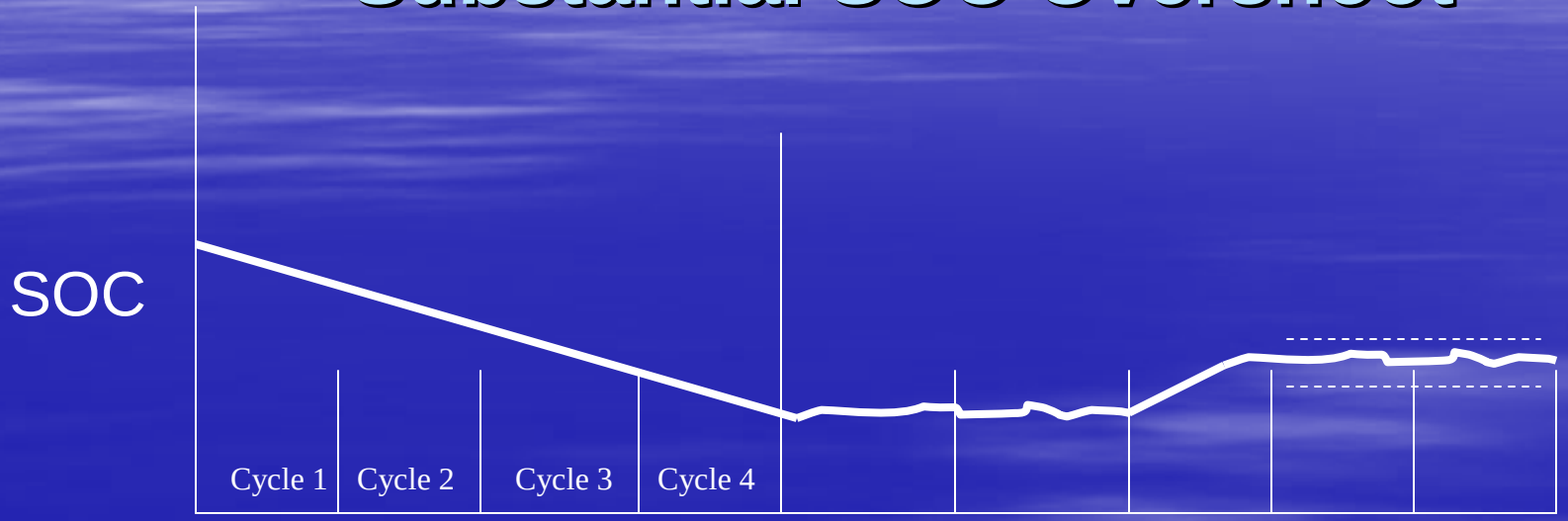


Minimal SOC Overshoot



End of Test Conditions (Cont.)

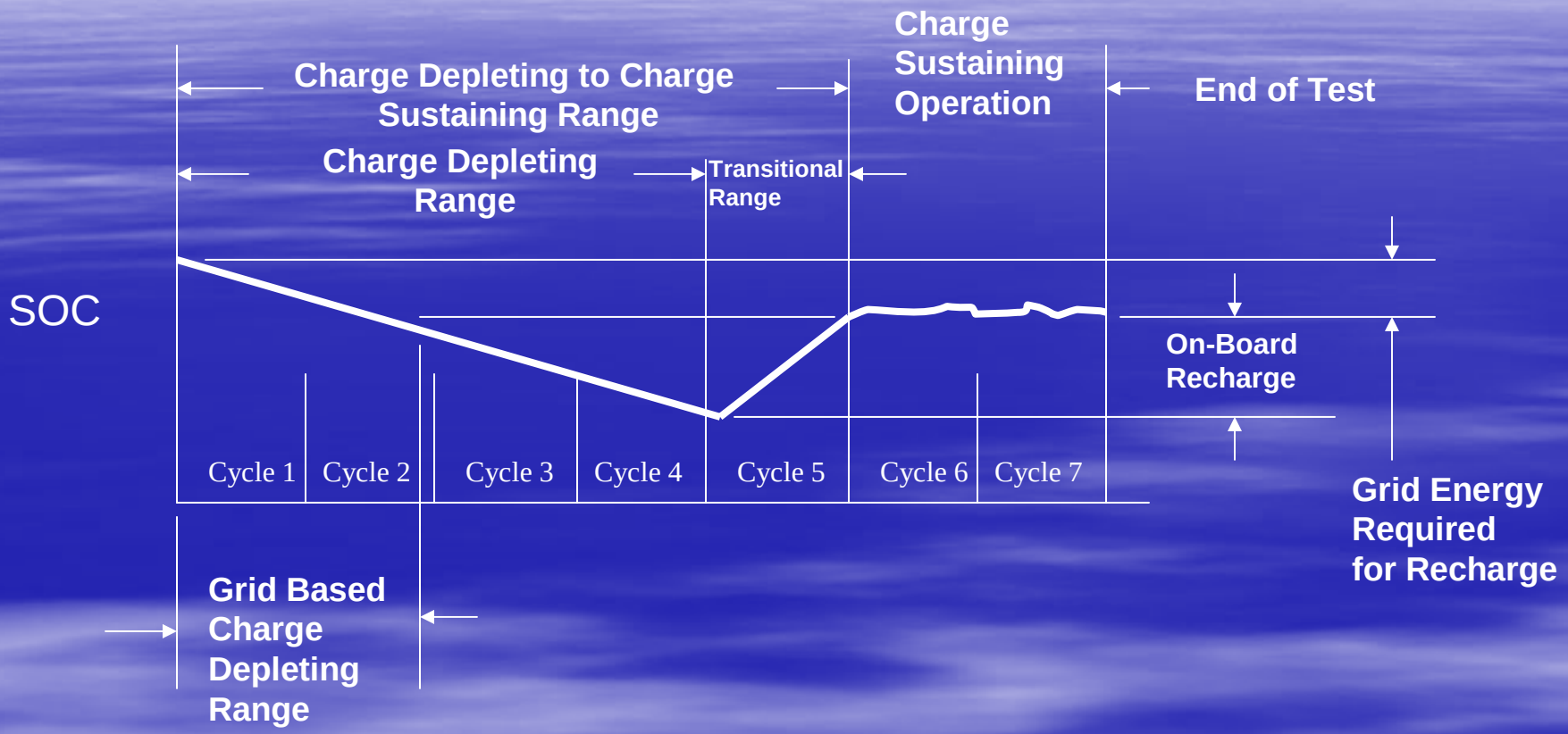
Substantial SOC Overshoot



In this condition, the OEM must inform us that it has a recharge mode

End of Test Considerations

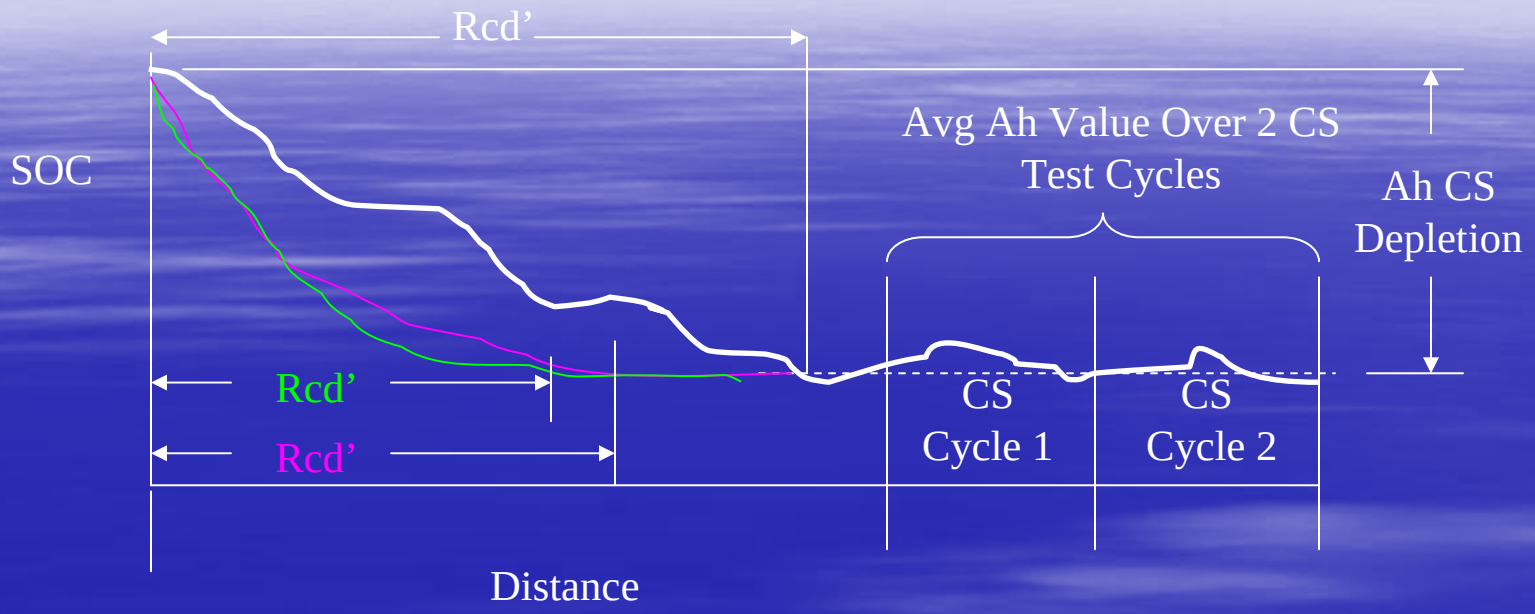
Substantial SOC Overshoot



At what point would On-Board Recharge?

- **Count against the charge depleting range?**
- **Defeat the purpose of wall charging?**

Determining Charge Depleting Range (Rcd) with Higher Resolution

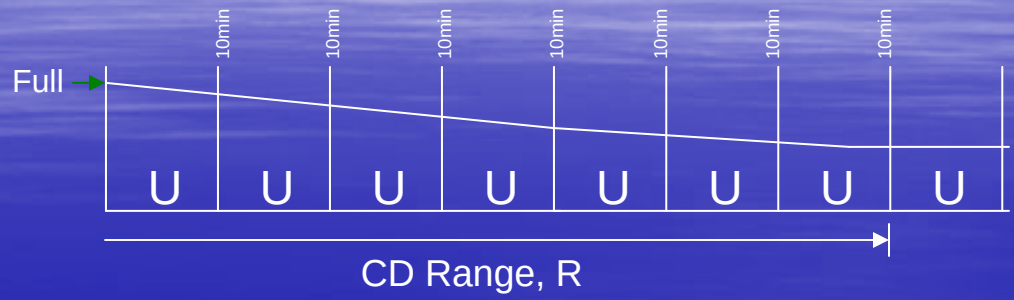


- **Using Net Amp Hour Discharge Method**
  - » **Quantitative method of determining battery discharge and range**
  - » **Sharper depletion rates ensure more consistent CD range results**
  - » **May not yield consistent CD range**
  - » **Possible use for Allowance calculation**
  - » **May need to differentiate between actual Charge Depleting Range & end-of-cycle Charge Depleting Range**
  - » **More testing required to determine method for high resolution Rcd**

Other High Resolution Rcd Calcs

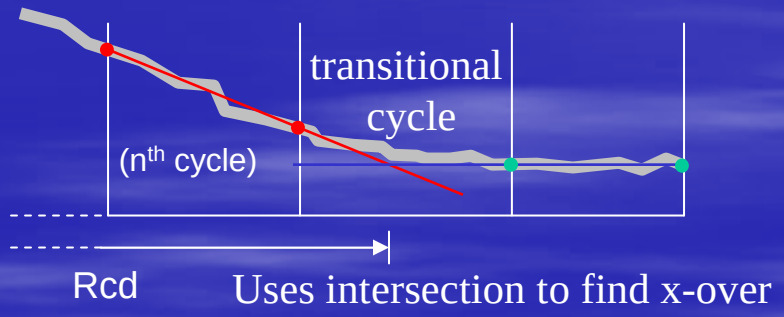
Graph 1- Rcd

- Integer number of cycles
- Poor resolution
- Good for UF calcs



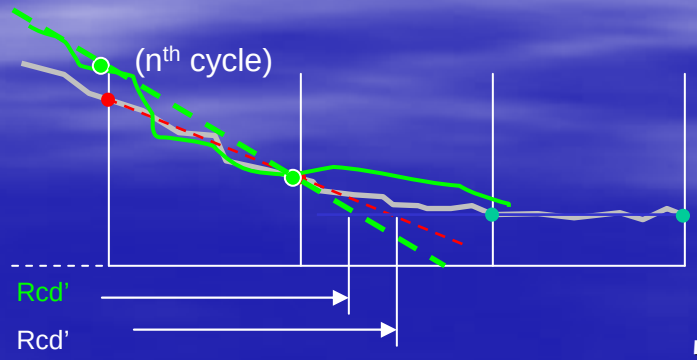
Graph 2 - Rcd

- Uses intersection to find x-over
- Good resolution
- Must discard transitional cycle data
- Good for calcs



Graph 3 - Rcd

- Better for asymptotic discharge profiles
- Dependent on discharge curve slope
- Variable



Other Issues

- **Range Confirmation test**
  - » Test to confirm ≥ 10 mile AER
  - » UDDS (US06?)
  - » End of test criteria
    - Vehicle cannot maintain speed & time tolerances of speed trace, or
    - Engine turns on
- **For HEVs (non plug in)**
  - » Eliminate references to setting battery SOC for CS tests
- **Electrical Measurement Accuracy**
  - » Overall error in recording instruments ≤ 2% (SAE J1634)
  - » Is 1% reasonable?
  - » Suggested equipment
    - Hioki 3193 power analyzer
    - Hioki 9278 clamp, and
    - Hioki 9602 Module
    - Accuracy may exceed J1634 requirements

Other Issues (cont.)

- **Watt Hour Calculation**
  - » $Wh = \int V(t) * A(t)\, dt$
  - » $Wh = \int OCV * A(t)\, dt$
- **Consumer Manual APU Activation**
  - » To ensure compliance with emissions standards in-use, manual activation of the APU by the consumer will be prohibited.
- **PHEV Testing**
  - » Need prototype, conversion PHEVs to validate and improve proposed test procedures

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Exhaust Test Procedure Discussion

Evaporative/ORVR Test Procedures

Ron Haste

Evap Change Objectives

Update evap regs/test procedures to reflect actual HEV architectures:

- Non-Plug-In
- Plug-In
  - » Blended
  - » Range extended

Current Evap Regulations

- LEV II Evap
  - » Adopted formally 1999
  - » Optional PZEV
  - » In-Use Verification Program
- Evap Tests
  - » Running Loss
  - » 3-Day Diurnal + High-Temp. Hot Soak
  - » Supplemental 2-Day Diurnal + Hot Soak
- On-Board Refueling Vapor Recovery (ORVR)
  - » Adopted 1995
  - » Integrated/Non-Integrated Systems

Current Evap Regulations (cont.)

- Evap stds
  - » Do not apply to HEVs w/sealed fuel systems that demonstrate no evap emissions
  - » Ref.: T13, CCR, §1976(b)(1)
  - » ORVR std still applies

Current Evap Regs (cont.)

- Test procedure requirements for HEVs:
  - » Specifying number of diurnals experienced before activating auxiliary power unit (APU) solely for purging evap canister
  - » Weighing canister to verify working capacity
  - » Specifying required purge time & analysis demonstrating purge within 5% of WC
  - » ref.: Evap TP, III.D.10.1.12 - 14
- Implicit intent is that HEV evap emissions are controlled for useful life

HEV Evap Issues

- Regs are Ok for most HEVs, except:
- Sealed fuel systems
  - » What is a “sealed” fuel system?
  - » How is “demonstration” performed?
- Current State-of-Charge (SOC) reqmt before evap 3-day diurnal test sequence is not “worst case” for PHEVs

HEV Evap Issues (cont.)

- Plug-In HEVs
  - » If end-users always “Plug In”
  - » APU never operates
  - » Evap canister never purges & emissions eventually become uncontrolled
- Is reqmt to activate APU solely for purging canister appropriate?
  - » Cold start exhaust emissions
  - » On-Board Diagnostic monitoring

Proposed PHEV Evap Stds.

- All 2010 & later MY PHEVs have “zero-fuel” evap emissions
- Similar to existing PZEV zero-evap reqmt:
  - » Zero-fuel emissions (54mg)
  - » “Whole” vehicle std (350mg)
  - » Non-integrated evap/ORVR system has zero-fuel diurnal emissions
  - » Mfr. must demonstrate how emissions will be controlled if end-users always “plug in”

Evap. Test Procedures Changes

- Modify test procedures to account for various HEV architectures
- Vehicle test sequences:
  - » Non-Plug-In HEVs
  - » Plug-In HEVs
- Plug-In HEVs:
  - » "Sealed" fuel system cert path
  - » "Non-Sealed" fuel system cert path

Test Procedures Changes:

Sealed Fuel Systems

Definition of a “sealed” fuel system

- Has zero-fuel evap emissions
  - » All systems, including ORVR
  - » Including permeation emissions
- Demonstrated by performance
  - » ARB’s MAC 2005-03 (PZEV demo)
  - » Using a “test rig”
  - » Other proposed demo methods allowed

Test Procedures Changes:

Non-Sealed Fuel Systems

- When manuf. activates APU solely for canister purge:
  - » Cold-start emissions must be added back into total exhaust emissions
  - » Use “fractionalized” amount based on real-world data & statistical analysis
- Demonstrate that PHEV emissions are controlled
  - » “Implicit” intent is controlled for useful life

Test Procedures Changes:

Non-Sealed Fuel Systems

- Purge canister using FTP
- SHED test for manuf.-specified diurnals
  - » Any breakthrough ► Failure
- Do FTP
  - » APU doesn't activate ► Failure
  - » Add cold start exhaust emissions to total
- SHED test for 3-day diurnal
  - » Any breakthrough ► Failure

PHEV Test Procedures Changes:

"Worst-Case" ORVR Diurnal

- "Worst-case" refueling-induced diurnal test
- Non-integrated evap control systems
- Demonstrate 3-day diurnal compliance:
  - » Loaded ORVR canister
  - » 100% filled fuel tank
  - » No FTP & RL test dyno drives
- LEV II evap std
- PZEV "whole" vehicle & zero-fuel test rig

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Evap Test Procedure Discussion

Proposed Schedule

Individual meetings with stakeholders	Now - July
2nd Workshop	Early June
Staff Report Published	Late August
Board Hearing	October 23, 2008

Summary

- PHEVs are substantially different from traditional vehicles
- Test Procedure modifications are needed for
  - » Exhaust & Evap
  - » To address all PHEV architectures
  - » To determine emissions
  - » To determine ZEV credit

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